Possible Impacts of Tidal Refluxing on Southern Puget Sound Benthos

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Introduction

We were motivated by 20 years of class projects at Shoreline Community College in which the sediments at 488 stations throughout Puget Sound were sampled and analyzed (1976 – 1996). Regional survey maps showing the ratio of empty benthic shells to those containing live specimens, drew our attention (Figures 1, 2, and 3). *Psephidia lordi*, for example, an important food item for English sole, was commonly found living north of the Tacoma Narrows, but in Southern Puget Sound was evident primarily as empty shells (Figures 2 and 3). In this paper, we explore the hypothesis that Southern Puget Sound's unique circulation produces this benthic anomaly.

A cursory oceanographic inspection placed Southern Puget Sound in regional perspective. Consider the rate at which upwelled water cycles through Puget Sound. The upwelling time scale of a given water body may be expressed as $T = V/Q$, where V is the basin's volume, and Q is the horizontal transport which upwells in the vicinity of mixing zones (Table 1).

The resulting time scale (10 days; Table 1) is the interval in which the South Sound's deeper water upwells into its upper layers. Since much of the upper layer lies within photic zone, refluxing rapidly raises deep, nutrient-rich water into shallow depths where plankton grow. Though Southern Puget Sound contains only 9% of the Puget Sound's overall volume, its waters are more highly refluxed than in any other major Puget Sound subdivision (Main Basin, Whidbey Basin, Hood Canal). Therefore, South Sound appears to us as an archipelago of interconnected water bodies with a unique collective behavior.

Table 1. Upwelling time scales (T) for Puget Sound basins. The regions have been ordered by time scale. Notation: the upwelling scale $T = V/Q$ (see text); and B, C, D, E, denote regions and associated volumes computed by McLellan (1954). Transport estimates are from Cokelet et al. (1990).

Puget Sound Region	Upwelling Time Scale (T, days)	Volume (V, km^3)	Upwelling Transport (Q, m^3/s)
Southern Puget Sound (C)	10	16	20,000
Main Basin (B)	60	77	15,000
Whidbey Basin (E)	110	29	3,000
Hood Canal (D)	120	25	2500

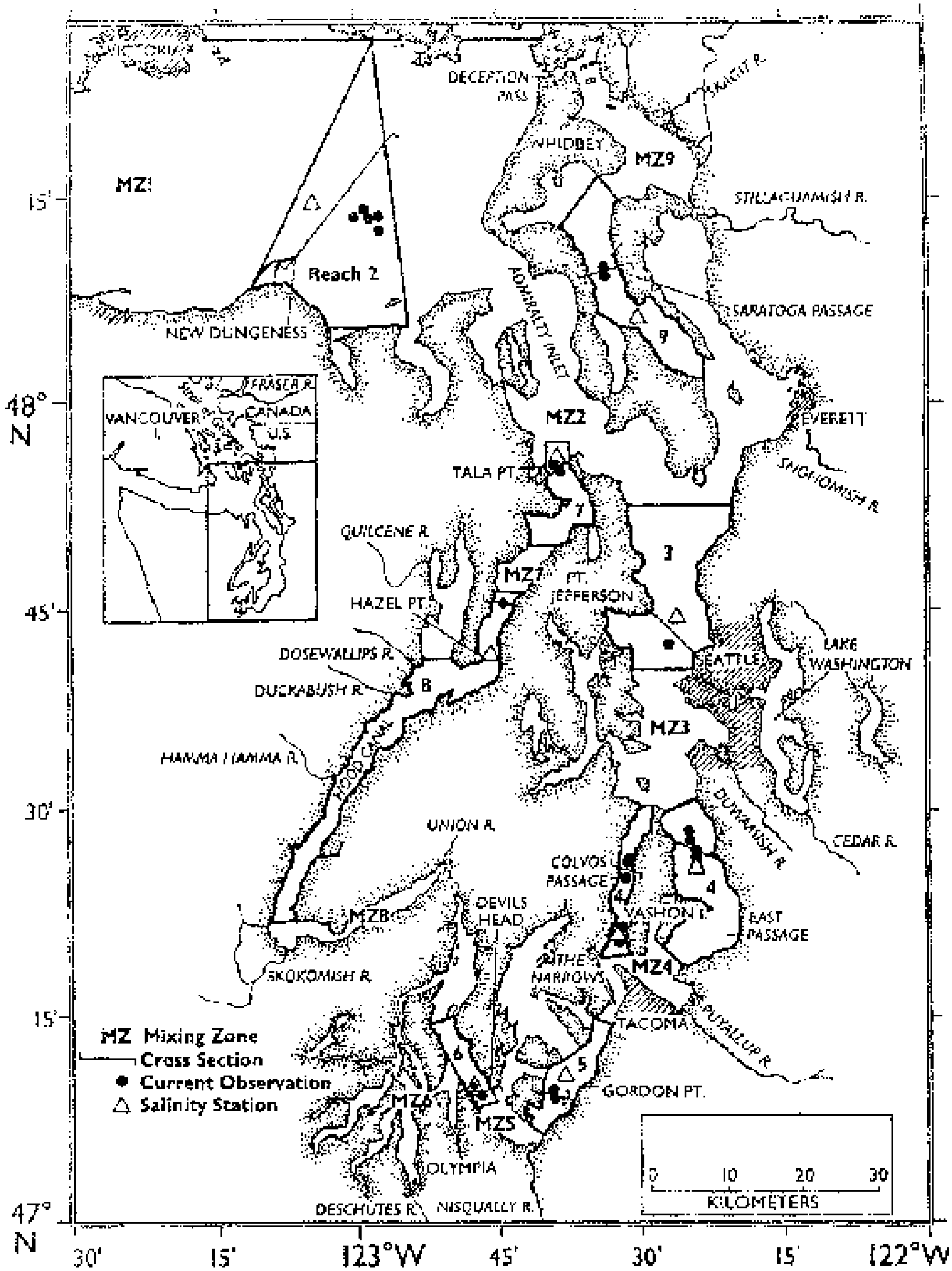

Figure 1. Reaches and mixing zones of the Juan de Fuca Strait/Puget Sound estuary (from Cokelet et al., 1991). Bold outlines denote reaches; mixing zones are labeled MZ. See Figure 2 for a 3-D view of the Sound's circulation.

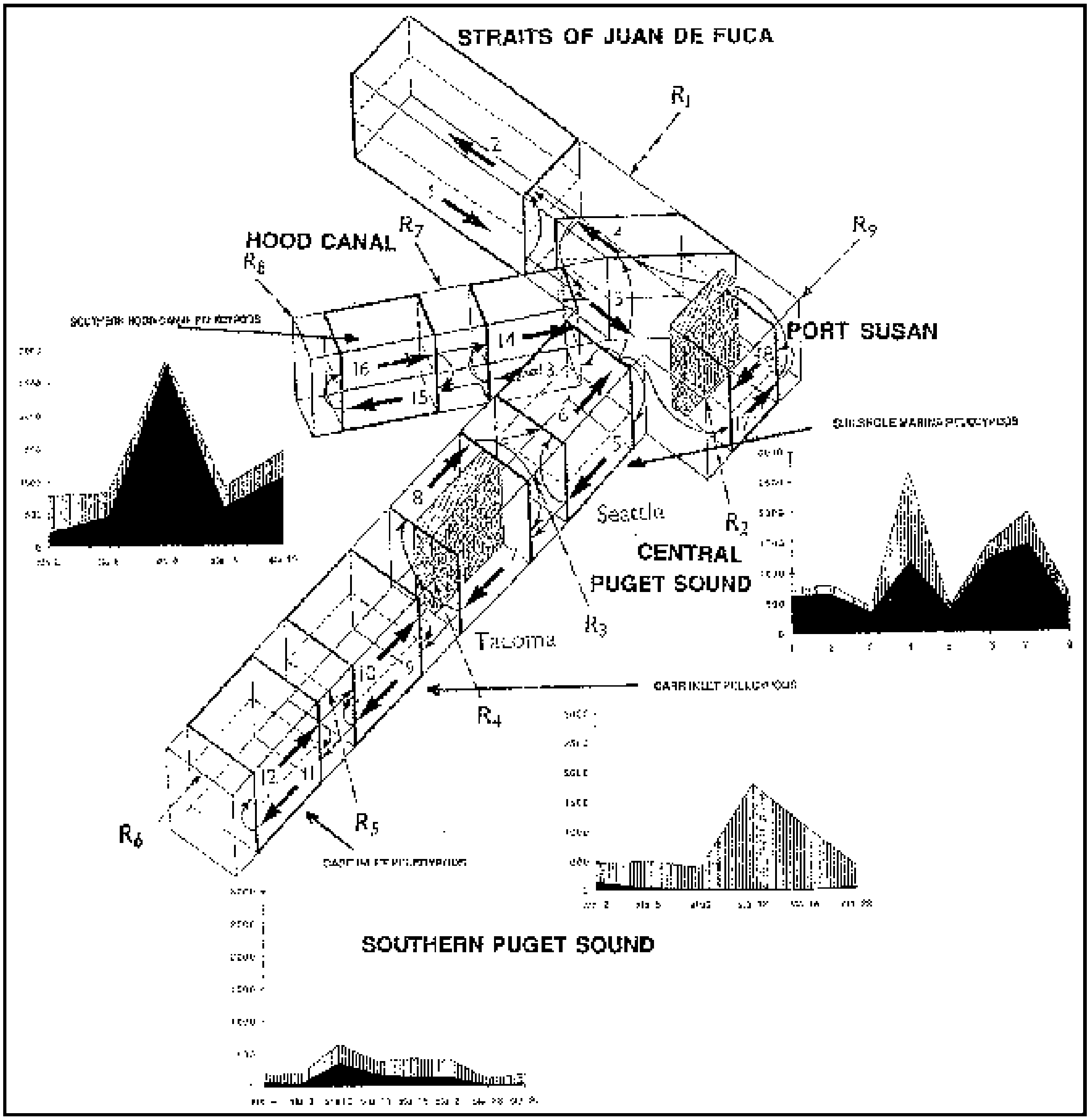

Figure 2. Puget Sound circulation compared with benthic shells. The circulatory schematic indicates flow direction in the 18 layers comprising Puget Sound (from Cokelet et al., 1991). See Figure 1 for locations of the flow reaches 1-18. Inset panels show numbers of empty shells and live pelecypod specimens at stations from benthic surveys conducted by Shoreline Community College in four areas: southern Hood Canal; Shilshole Marina in the Main Basin; and Carr and Case Inlets in southern Puget Sound. Note that compared with the Main Basin and Hood Canal, most of the shells in southern Puget Sound were empty.

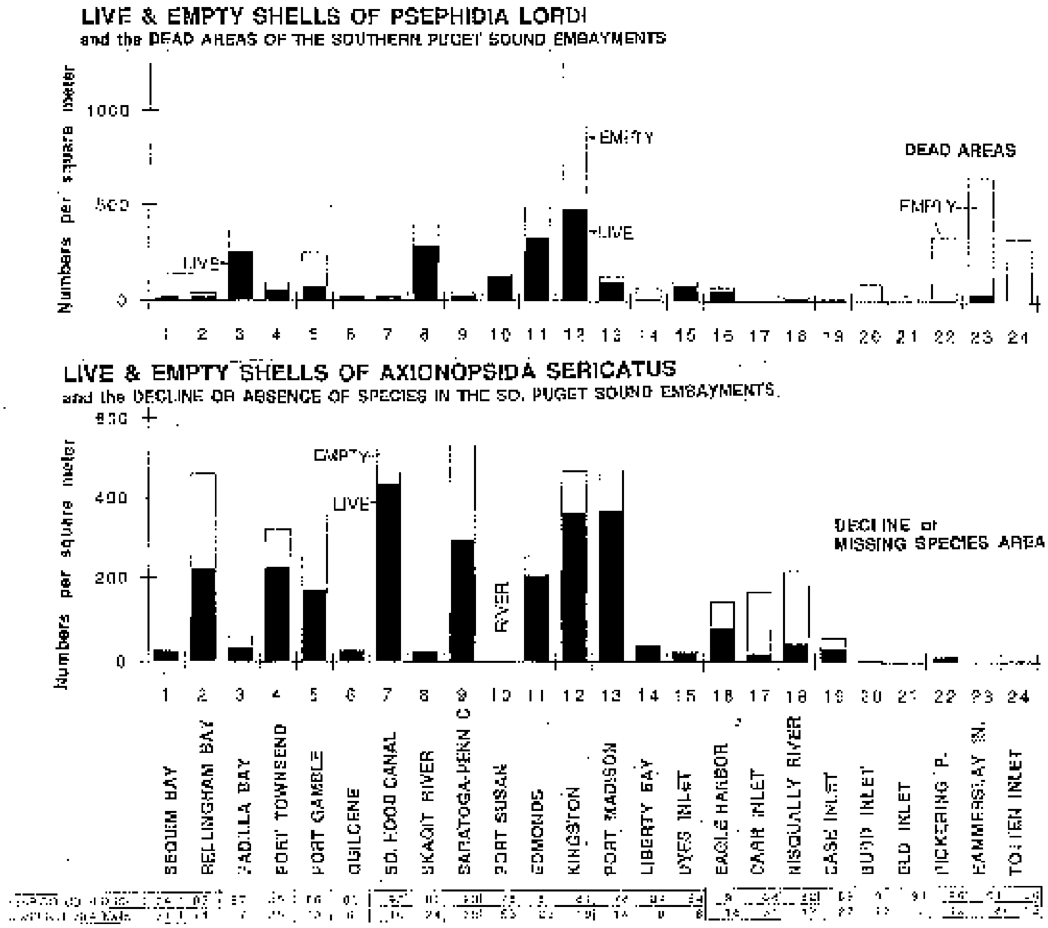

Figure 3. Live and empty shells from benthic surveys (*Psephidia lordi, Axionopsida sericatus*). Each bar represents the average number of live specimens (darkened) and empty shells (open) found in a given survey. The 24 areas surveyed and associated numbers of benthic stations, are provided at bottom (please consult Puget Sound atlases for locations). The bars are laid out approximately along the main axis of the Juan de Fuca Strait/Puget Sound estuary with the following area groupings: areas 1–4, Juan de Fuca Strait and approaches; 5–7, Hood Canal; 8–10, Whidbey Basin; 11–16, Main Basin; 17–24, Southern Puget Sound. Note the marked drop off in fish food abundances of *P. lordi* and *A. sericatus* south of the Narrows.

Methods

Benthic samples

Benthic samples obtained in 24 surveys during 1976 –1996 were examined. These surveys were designed to sample benthic species in the deeper waters and not the intertidal areas. Please consult Puget Sound atlases for locations of the many places surveyed.

The samples were collected with a 0.1-m^2 van Veen grab sampler and washed through a 1-mm screen. Washed residues were preserved in a 10% formaldehyde solution using rose bengal stain. Within days after each survey, the samples were sorted under a magnifying lamp by taxa and preserved with a glycerin-alcohol solution. While sorting, the number of empty whole shells was estimated as half of the umbo portion of the pelecypods (umbo: elevated knob near the ligament on each valve of a bivalve). The numbers of live and empty shells of all pelecypods were enumerated.

Refluxing

The Puget Sound Refluxing (PSR) model represents Puget Sound as a network of advective reaches linked by mixing zones (Figures 1 and 2). Within the mixing zones, reflux parameters determine the distribution of the inflowing water into the outflowing reaches. The model has been successfully applied to explain the changes in observed copper concentrations that resulted from improved sewage treatment in the 1980s (Paulson et al., 1992).

Synthesis

The network of reaches and mixing zones, together with the refluxing between adjoining reaches, determines the distribution of salt and fresh water within Puget Sound. By combining historical observations of currents, salinity, and freshwater inputs, estimates of the transport and transit times were determined for each of the 18 reach layers comprising the PSR model (Figures 1 and 2; Cokelet et al., 1990). The observed salinities were then used to compute reflux coefficients for each of the layers feeding into a given mixing zone. In addition, transit times for the mixing zones were computed based on the zone's volume and associated transports.

Although the PSR model is based on long-term averages, and does not specifically address time-varying processes, the transit times and transports do provide time scales for the flushing of chemicals introduced into Puget Sound. Specifically, the transit time, volume transport, and reflux parameters may be mathematically combined to estimate both the amount flushed from a given region and that remaining after the introduction of a tracer at a given location.

Because Puget Sound contains multiple mixing zones wherein a portion of the outflowing surface layer is refluxed back into the system, there are numerous pathways between given locations. If we represent Puget Sound as a set of simultaneous equations, we may solve them for the concentrations measured at the exit of each of layer as a time-varying quantity that depends on the concentrations in the source layers. By solving 18 equations for each time step, the effect of the transport processes in distributing input throughout the Sound may be computed.

Flushing and Retention

The question is often asked: "How long will it take to flush the material from the Puget Sound system?" Given that introduced material will be refluxed throughout the Sound's reaches, and the degree of refluxing varies with location, "flushing" times may be defined in several ways. In this paper we focus on two definitions, each dealing with the response of the Sound to a conservative tracer introduced at a steady rate over a period of three days. Since the time scales of the individual reaches vary between approximately 10 to 20 days, and the scale of the system is about 100 days, in practical terms, this input is an "impulse."

The first definition is a Puget Sound-wide flushing time. It is the interval required to remove material from Puget Sound by transport to the Pacific Ocean from Juan de Fuca Strait. Figure 4 shows the times for the impulse to be removed from four different reaches. The first site is the surface layer at Point Jefferson, which receives the effluent discharged from the Metro/King County West Point outfall. It flushes the most quickly of all, with 50% of the material removed after approximately 90 days.

The second site is in Colvos Passage. Its flushing is similar to that from the Point Jefferson site, except its response lags that of the Elliott Bay/Alki Point mixing zone, and a small amount of Colvos Passage material refluxes into East Passage. The third site is the lower (inflowing) reach at Devils Head within Southern Puget Sound. It can be seen that both the Colvos Passage and Devils Head reaches require about 120 days before 50% of the material is removed via transport out Juan de Fuca Strait. The fourth site is the lower reach of the inner arm of Hood Canal, which is labeled Hazel Point in the PSR model. Hood Canal is widely understood to be the slowest-responding branch of Puget Sound, and Figure 4 supports this hypothesis.

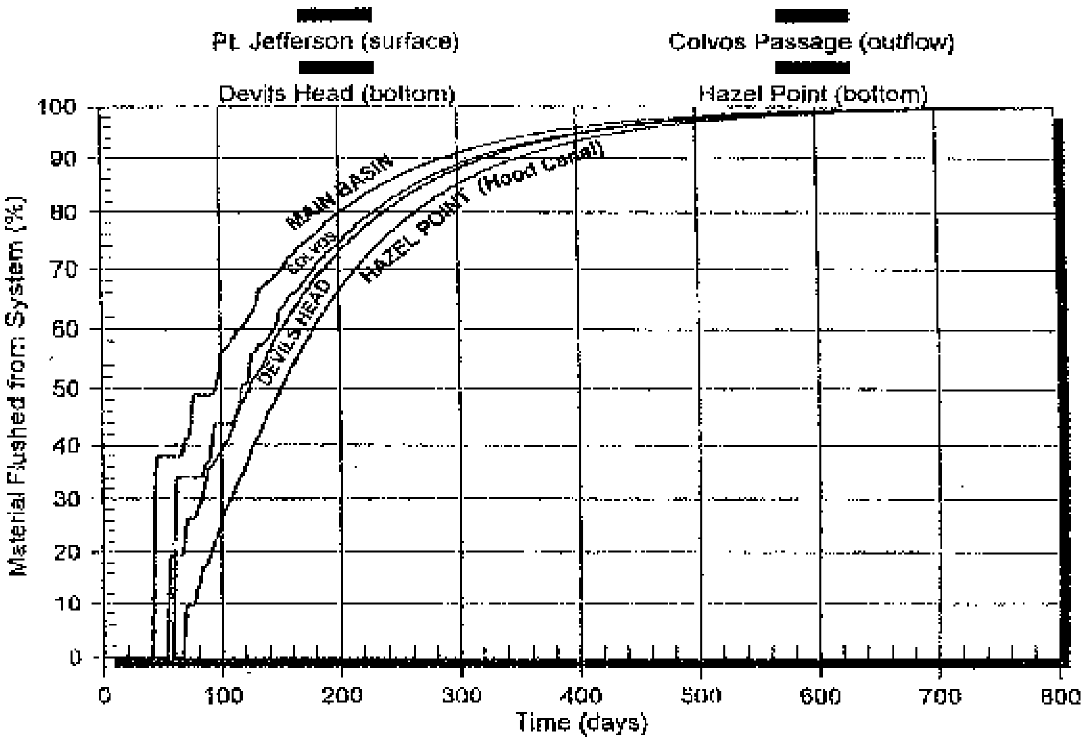

Figure 4. Flushing of a three-day step input from four areas of Puget Sound. Comparison of alternate input locations.

The second flushing definition deals with the amount of time required to remove the material from the branch of Puget Sound in which the material is introduced. This flushing is complicated by the inland refluxing of material. For the Point Jefferson site, the relevant measure is the amount of material that remains within the Puget Sound system including the input site, the lower layer reach beneath the input site, and the three pairs of reaches extending southward to Devils Head. The measure used for the Devils Head input involves the material retained inland of the Tacoma Narrows and thus includes the Gordon Point and Carr Inlet regions. The Hood Canal site is characterized by material retained in the Hazel Point reaches. The Colvos Passage input site was also investigated; for clarity it is not included in Figure 5.

A striking aspect of Figure 5 is the large amount of material retained in Southern Puget Sound for releases in the Devils Head reach. It can be seen that 20 days after the introduction of the conservative tracer, the model predicts 50% of the material will be retained in the Gordon Point-Carr Inlet area and Devils Head reaches. The amount of material drops off to 14% at 50 days and decays exponentially thereafter. In contrast, if the material is introduced in the upper layer at Point Jefferson, it is quickly transported into the Admiralty Inlet mixing zone, and thereafter the total material returned to the inland reaches never exceeds about 31% of the initial dose.

The comparison shown in Figure 5 is more striking if we consider the water volume in which the material may be dispersed. The 31% retention at Point Jefferson is distributed over all the Main and Southern Puget Sound basins, whereas the material retained from the Devils Head site is dispersed only over the finger inlets. McLellan (1954) lists the volume of the Main Basin at 12.1 cubic nautical miles (76.9 cubic km) and that for Southern Puget Sound as 2.5 cubic nautical miles (15.8 cubic km.) The divisor for the Point Jefferson discharge is therefore 14.6 cubic nautical miles versus 2.5 for Devils Head.

Thus, the Southern Puget Sound region differs from the Main Basin in both the quickness with which the lower layer waters are refluxed into the upper layers, and in the relative slowness of the removal process.

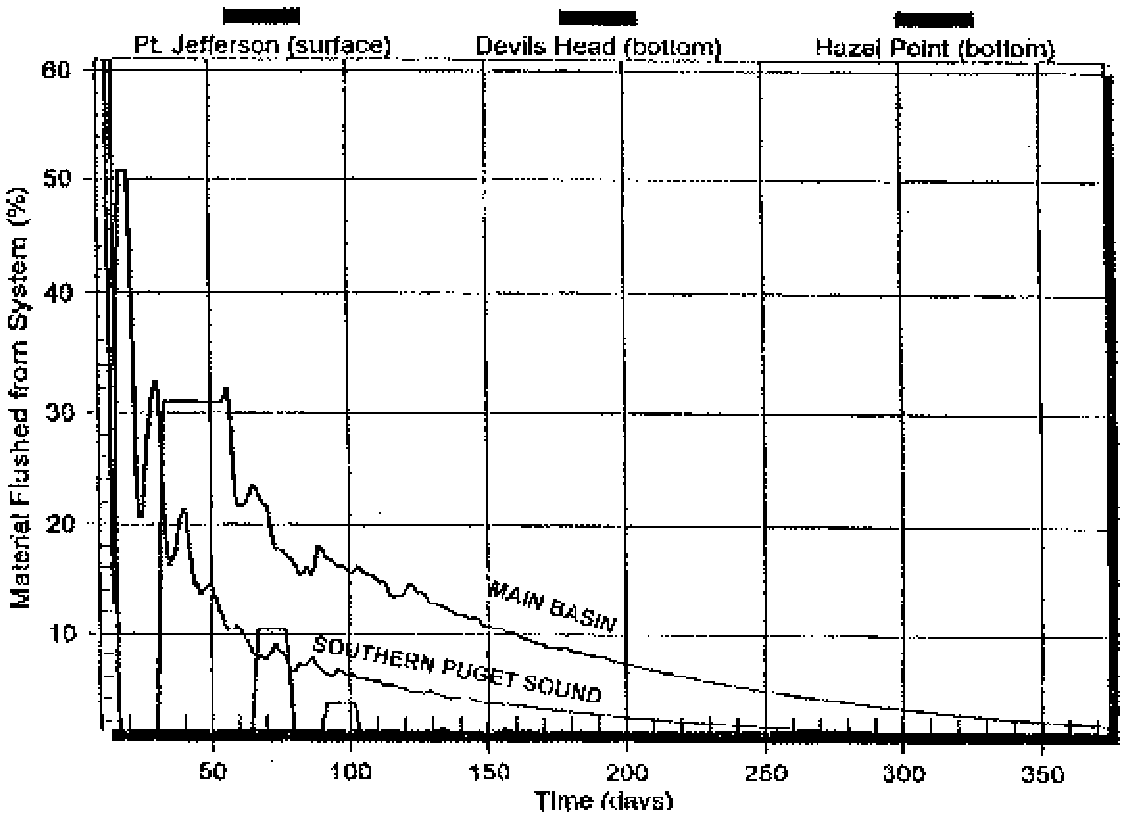

Figure 5. Retention of a three-day step input from three areas of Puget Sound. Comparison of alternate input locations.

Refluxing Model and Benthic Biology

Pelecypod counts of living and empty specimens north of the Tacoma Narrows sill typically have higher numbers of living to empty shells than those of Southern Puget Sound (Figures 2 and 3). Shilshole Marina samples, where sediments contain high concentrations of oil and metal debris, have greater live counts and a more diverse fauna than those of the Southern Puget Sound. Even in the southernmost portions of Hood Canal, subtidal sediments exhibit comparatively high live-to-empty shell ratios, as well as many species absent in South Sound.

Previously, Harman and Serwold (1977) found that, based on the benthic foraminiferal distribution, the sills in Admiralty Inlet blocked the deep water organisms of Juan de Fuca Strait from entering the Main Basin (e.g., *Cassidulina californica, C. reflexa)* or significantly reduced their concentrations (e.g., *Uvigerina juncea*, *Globobulimina auricula*, *Epistomenella pacifica)*. Sediment cores obtained by Dr. Fred Nichols from mid-channel off West Point contained none of Juan de Fuca Strait species. Furthermore, the pectinarians which Nichols began studying in the 1970s were no longer present in the 1990s.

The sensitivity of benthic organisms to degraded sea bottoms in Southern Puget Sound shows similar trends to that of the Puget Sound salmon pen farms located at varying distances from Juan de Fuca Strait. The more oceanic-influenced Skagit Bay fish farm contains many of the shallow water mud-loving species (e.g., *Ascila castrensis, P. lordi* and *Axionopsida sericatus*. These species are absent in the more impacted southern farms or basins (Figure 3).

The sensitivity of *A. sericatus* and *P. lordi* is illustrated in the decline in their concentration toward the pen edge and most significantly in their decline and present-day absence from the farms (Figure 6). Perhaps the difficulty in maintaining their population is associated with their brooding mode of reproduction, which may make recruitment by pelagic larvae impossible. Some pelecypod species—such as *Mysella tumida* and *Parvulucina tenuisculptus*, which also dominate the less diverse benthic faunas of the deep Southern Puget Sound basin—respond favorably to the salmon pen organic loading of bottom sediments.

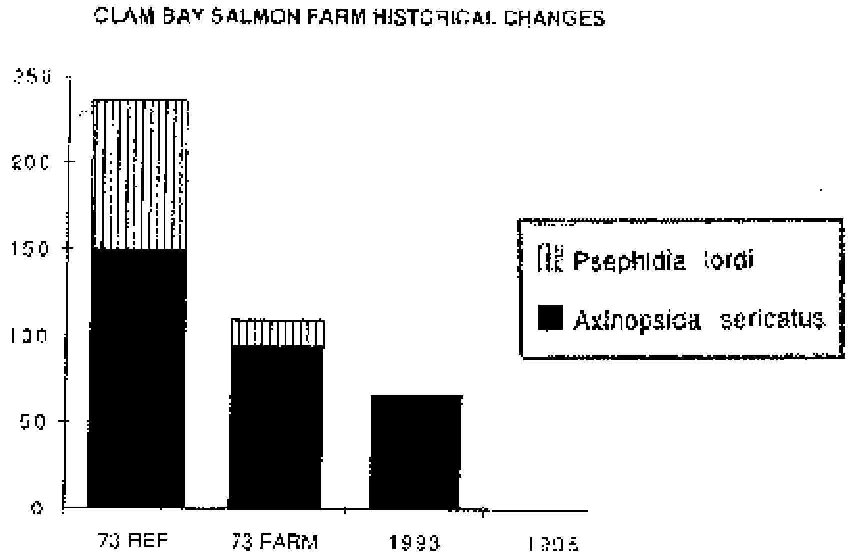

Figure 6. Historical changes in live concentrations of *Psephidia lordi* and *Axionopsida sericatus* over Clam Bay salmon pen sites. Data from Mahnken (1993) and Brooks (1992, 1995).

Unpublished Shoreline Community College analyses indicate significant declines in other species south of the Tacoma Narrows, as well as reductions in nearshore species such as the ostracod *Euphilomedes spp*, and the sedentarian polychaete *Phyllochaetopteran prolifica*. This polychaete forms chitinous worm tubes which provide substrates for tunicates, sponges, foramninifera, scallops, and sea cucumbers. Mahnken (1993) indicated their dominance at his reference site but described their absence and presence as empty tubes at a former fish farm site. These polychaetes have not yet returned to the Clam Bay farm site.

The organic loading at the salmon pens obviously impacts areas beyond the "200-foot Reference Site" based on the abnormal dominance of *Capitella capitata* for tidal channel habitats. Strong currents in Rich Passage could transport the same organics that cause the farm declines into adjacent depositional sites of Yukon Harbor where *A. sericatus* occurs. This is suggested by rock-attaching arenaceous foraminifera, *Trochammina carlottensis*, present in Rich Passage that are dispersed into Yukon Harbor as well as being the ultimate settling site for the pelagic diatom, *Coscinodicus spp*.

The refluxing of river sediments is expected to cause greater sedimentation due to longer residence times. This phenomenon appears to be exemplified by lower-sediment concentrations of the pelagic diatoms *Coscinodiscus spp* in Port Susan (less than 50 frustules/ gram sediment) compared with those in the Main Basin and Hood Canal (greater than 200 frustules/gram sediment). The strong currents in tidal channels or sill areas such as Rich Passage, Colvos Passage, Tacoma Narrows and Nisqually Reach result in concentrations less than 5 frustules/gram sediment compared with nearby depositional sites. Thus, suspended and sea bottom debris is transported by currents creating organic-rich sediment.

Conclusion

We struggled to unite physical refluxing and benthic ecology because the collective data suggested to us that South Sound's high level of refluxing is recycling introduced materials, which in turn impact the benthos south of the Tacoma Narrows. Despite our efforts, it is not known whether retention effects associated with refluxing are significant. Longer exposures to pollutants due to slower flushing in

Southern Puget Sound may negatively affect benthic populations. Given the distressed condition of selected benthic populations suggested by the Shoreline Community College benthic surveys, future studies should address the underlying toxicological reasons for these declines, particularly concerning the dispersal of brooding benthic species.

Acknowledgements

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